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The role of loamy sediment (*terra rossa*) in the context of steady state karst surface lowering

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ABSTRACT

Reddish, loamy material (*terra rossa*), found on many karstified surfaces, has long been accepted as a characteristic karst feature. Two basic views of *terra rossa* formation were distinguished, related to either a residual or a detrital origin. More recently it has been suggested that it could derive from isovolumetric reactions between the parent carbonate rock and airborne material. This paper reviews possible sources of *terra rossa*, explores its behaviour on the karst surface from the karst geomorphology viewpoint, and considers whether its existence is better explained in terms of a closed or open karst geomorphic system. Two approximately west–east traverses were laid out across Slovenia and the Czech Republic, comprising nine sample locations in each country previously known to be characterized by *terra rossa*. General geomorphic/speleomorphic conditions were estimated, and loamy material and parent rock samples were collected. Insoluble residues extracted from the rock were processed in the same ways as the loamy material. Basic geochemical and mineralogical investigations were run. The data obtained were processed statistically. Results show that statistical relationships between the adjacent rock insoluble residues and adjacent *terra rossa* bodies exist only at sampling sites recognised as "vertical". Most such sites are cutters, which are "karren-like grooves formed beneath the soil, more commonly referred to as subsoil karren" (US Environmental Protection Agency, 2002. A Lexicon of Cave and Karst Terminology. Field, M.S. (Ed.). <http://www.karstwaters.org/files/glossary.pdf>, p.53).

Possible sources of *terra rossa* material as well as the possibilities of material accumulating on the karst surface are discussed in detail, with special emphasis upon cutters. Theoretical considerations indicate that cutters are the only features that can collect sufficient insoluble residue to be detectable after a period of evolution within a surface that is lowering under steady state conditions. All other accumulations of similar appearance must be admixed materials of diverse origins or be completely allogenic in origin. The most recent approach, which considers *terra rossa* as an active karst surface agent, is temporarily put aside, though its explanatory potential in the future is acknowledged.

1. Foreword

Since the introduction of general systems theory in geomorphology several decades ago (Chorley, 1962; Chorley and Kennedy, 1971) earlier paradigms (see Summerfield, 1991, pp. 457–463) have been abandoned and empirical knowledge about the Earth's surface landforms (Summerfield, 1991, pp. 464–466) has been adapted to new views. Within this context the principle of landscape sensitivity (Summerfield, 1991, p. 465) became crucial. In practice, it reduces to the question of whether particular sets of predominating, characteristic, landforms in a chosen area are time dependent or whether they have achieved a time independent state (Summerfield, 1991, p. 467, Fig. 18.9), or climax state (sensu Garner, 1974, p. 697).

Ford and Williams (1989) intentionally adopted a systems approach (and expanded it in the revised, 2007, edition of the same book). Šušteršič (1996) offered the "Pure Karst Model" (PKM), which is largely a reworking in open system terms of Grund's (1914, republished 1981) model. The system would achieve its ultimate expression when the parent rock is absolutely free of insoluble components if the structure permits vertical drainage at all.

Considering mass transport, the fundamental characteristics of the karst geomorphic system (summarized after Šušteršič, 1996, pp. 28–30; Ford and Williams, 2007, p. 321) are:

- mass removal in the form of solution
- no surface accumulation of released material (regolith in the widest sense)
- vertical outflow of the precipitation water (including dissolved mass).

These (and a number of other) authors emphasise that the pre-existence of underground karstification conditions the formation of surface karst phenomena.

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The almost total absence of surface transport material and the effects of mass removal perpendicular to the surface make relaxation times much longer than those associated with other geomorphic systems. A number of the surface karstic phenomena remain in the time-dependent, i.e. transitive, stage for long periods. Only recently have computer simulations (Dreybrodt and Gabrovšek, 2002) revealed that in some cases steady state conditions may be achieved relatively quickly (Gabrovšek, 2007).

In this context the mere existence of insoluble material is, at best, intrusive. The karst would transmit mass best without any interference from insoluble material. Nevertheless, the ubiquitous occurrence of reddish, loamy material (popularly called *terra rossa*) on many karstified surfaces, is widely accepted as characteristic of karst terranes.

The present paper aims to explore possible sources of such material, and to consider whether its existence is better explained in terms of a closed or open karst geomorphic system, with the proviso that lack of proper field data precludes full consideration of the recent findings of Merino and Banerjee (2008).

2. Introduction

The expression "terra rossa" was first used by Tućan (1912, cit. Marić, 1964) in the Mediterranean region. It derives from an Istrian (presently Croatia) Italian dialect, and equates with the strikingly red soils in the otherwise heavily karstified Istria.

The Lexicon of Cave and Karst Terminology (US Environmental Protection Agency, 2002, p. 191), offers two definitions of *terra rossa*:

1. *Reddish-brown soil mantling limestone bedrock; may be residual in some places.*
2. *Insoluble residuum of a reddish-brown colour left behind when carbonate rocks weather under Mediterranean or allied climatic conditions.*

Realizing that such definitions contain hidden presumptions Merino and Banerjee (2008) offered an apparently looser but more general definition (Merino and Banerjee, 2008, p. 62): "Terra rossa clays are red claystones up to several metres thick and kilometres across that occur at the earth's surface and are associated with karst carbonates." They noted (Merino and Banerjee, 2008, p.64) that "… additional subtle problem may be that terra rossa is often referred as "terra rossa soils", a term that, in effect, takes for granted that the genesis of terra rossa clays is pedological by definition."

Since the recognition that *terra rossa* is somehow connected with the karst (rock), two nearly mutually exclusive alternative explanations of its origin, namely the residual and the detrital, have survived. The former (Tućan, 1912) appears to be somewhat earlier and seems to have prevailed up until the present (Neuendorf et al., 2008), though bauxite researchers in particular (Comer, 1974, 1976; Guendon and Parron, 1985) provided serious support of the latter. (Merino and Banerjee, 2008, pp. 62–64 provide an up-to-date review). Rousset (1967) noted the influence of the karst environment upon *terra rossa* formation.

Merino and Banerjee (2008) showed that, in their study cases, *terra rossa* is a product of interaction between the parent rock and airborne Si, Al and Fe. So, *terra rossa* formation is one of the active surface karst forming processes. Evidently, assimilation would continue only until Si, Al and Fe ions derived from volcanic ash were consumed. Thus, the question remains, to what extent can their findings be generalized?

In contrast reaction fronts, which they studied in detail, appear to be virtually ubiquitous. The explanation, most common among karstologists is, that mere existence of larger loamy bodies on the karst surface encourages more vigorous vegetation and, consequently, enhanced soil CO_2 production that would in turn enhance rockhead corrosion (Gams, 1981). Processes, revealed by Zupan-Hajna (2003) in cave wall formation, appear to be just a generalization of the Gams' explanation. Despite these earlier views, Merino and Banerjee's (2008, p. 64) recent claim that reaction fronts have only now been studied and understood in sufficient detail suggests that this aspect now deserves fuller consideration.

In view of the reservations expressed above, Merino and Banerjee's (2008) ideas are not examined in detail here. Instead, the present authors consider widely accepted karstologists' views (Gams, 1981) that the mere existence of larger loamy bodies influences development of some surface karst phenomena while *terra rossa* material remains chemically inert. Within a basic consideration of two alternative mechanisms of *terra rossa* origin, two questions are posed:

i) which surface and underground karstic forms do the (studied) occurrences of *terra rossa* rely upon?
ii) do such phenomena provide any information about whether the general conditions are more readily attributable to an open or to a closed geomorphic system?

Before going further an important point must be made: if (in terms of the residual origin hypothesis) any relationship exists between the clayey fraction and the insoluble residue of the parent rock, the mineral composition of the former will not directly mirror that of material extracted from currently adjacent rock. Instead it will reflect the composition of formerly overlying rocks that have been removed by denudation. In such circumstances, it is sensible only to search for approximate similarities. Even if a mineral composition similar to that of the parent rock insoluble residue is confirmed, as in some *terra rossas*, the possibility of coincidental similarity cannot be excluded.

3. Materials and methods

Though the total number of *terra rossa* studies is enormous, information about the prevailing geomorphic conditions is sparse. In view of this limitation two approximately west–east traverses were laid out across Slovenia and the Czech Republic (Fig. 1), comprising nine sample locations in each country. The former traverse runs across the Dinaric Karst of southern Slovenia. Sample locations were spaced

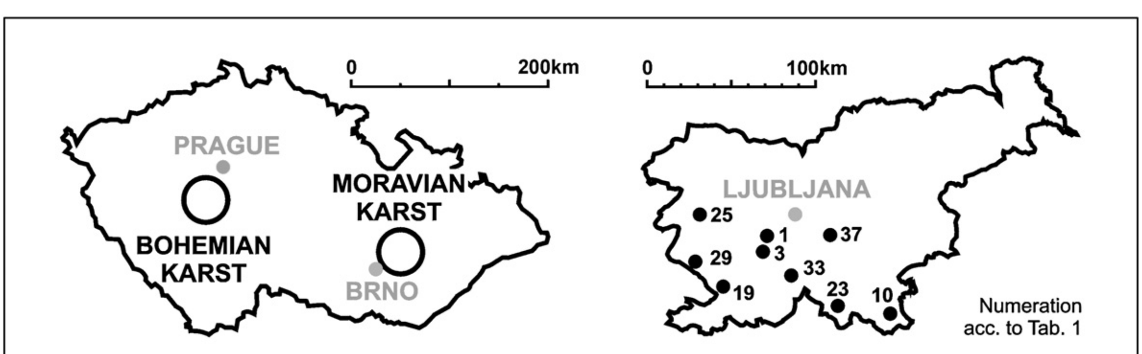

Fig. 1. Sampling locations. Numbers are as shown in Table 1. Note that in the Czech Republic only the sampled regions are shown, as individual sample sites are too close together to be marked individually.

Table 1
General sample location data

No. of location	Name of location	Country	Coordinates	Elevation asl	Parent rock	Mean ann. precip.	Mean ann. temp.	Denudation rate[a]	Color
1	Verd	SLO	14°19′E 45°57′N	410 m	Limestone $J_{1,2}$	1600 mm	8 °C	60–65 m Ma^{-1}	Red 2.5YR 4/8
3	Laze	SLO	14°16′E 45°51′N	470 m	Limestone K_1	1800 mm	8 °C	60–65 m Ma^{-1}	Red 2.5YR 5/8
4	Suchomasty	CZ	14°5′E 49°5′N	340 m	Limestone D_2	450 mm	8.5 °C	20–25 m Ma^{-1}	Red 10R 5/8
8	Březina II	CZ	16°45′E 49°17′N	420 m	Limestone D_3	630 mm	7.5 °C	20–25 m Ma^{-1}	Red 10YR 4/8
9	Malomeřice	CZ	16°42′E 49°13′N	380 m	Limestone D_3	570 mm	7 °C	20–25 m Ma^{-1}	Strong brown 7.5R 4/6
10	Tribuče	SLO	15°15′E 45°33′N	190 m	Limestone K_1	1250 mm	8 °C	65 m Ma^{-1}	Reddish yellow 5YR 6/8
13	Březina I	CZ	16°48′E 49°17′N	420 m	Limestone D_3	630 mm	7.5 °C	20–25 m Ma^{-1}	Red 10R 5/7
17	Skalka	CZ	16°45′E 49°17′N	460 m	Limestone D_3	630 mm	7.5 °C	20–25 m Ma^{-1}	Red 10R 4/6
19	Divača	SLO	13°59′E 45°40′N	450 m	Limestone K_2	1400 mm	>10 °C	20–30 m Ma^{-1}	Red to dark red 10R 3.5/6
23	Kočevska Reka	SLO	14°49′E 45°34′N	570 m	Dolomite T_3	1600 mm	8 °C	60–100 m.Ma^{-1}	Reddish yellow 7.5YR 6/7
25	Čepovan	SLO	13°48′E 46°3′N	660 m	Dolomite T_3	2400 mm	8 °C	60–90 m Ma^{-1}	Brownish yellow 10YR 6/6
26	Hostim		49°57 N, 14°9′E	320 m	Limestone D_1	450 mm	8 °C	20–25 m Ma^{-1}	Light red 10R 6/8
28	Tmaň	CZ	14°4′E, 49°54′N	390 m	Limestone D_1	450 mm	8.5 °C,	20–25 m Ma^{-1}	Red 10R 4/8
29	Komen	SLO	13°45′E 45°49′N	270 m	Limestone K_2	1500 mm	10 °C	20–30 m Ma^{-1}	Yellowish red to reddish yellow 5R 5.5/8
32	Tětin	CZ	14°6′E, 49°57′N	310 m	Limestone D_1	470 mm	8 °C,	20–25 m Ma^{-1}	Red 2.5R 4.5/6
33	Lož	SLO	14°29′E 45°44′N	660 m	Dolomite $J_{1,2}$	1500 mm	6 °C	65 m Ma^{-1}	Yellowish red 5YR 5/8
34	Sloup	CZ	16°44′E 49°25′N	490 m	Limestone d_{2-3}	680 mm	6.5 °C	20–25 m Ma^{-1}	Red 10R 4/6
37	Višnja Gora	SLO	14°46′E, 45°57′N	380 m	Dolomite T_3	1300 mm	>8 °C	20–40 m Ma^{-1}	Dark yellowish brown 10YR 4/6

[a] General average values. Note that detailed data about denudation rates are not available for individual locations in the Czech Republic.

approximately uniformly and were chosen in such a way that they cover the most important rocks of the Mesozoic carbonate sequence (continuous, from late Triassic to Palaeocene, and totalling about 7 km in thickness / Šušteršič, 2000). In the case of the Bohemian and Moravian karst areas, which are not continuous (Herak and Stringfield, 1972), samples were taken from locations previously known to be characterized by *terra rossa*. An additional sample of *terra rossa* was taken at Umag (Istria, Croatia) in order to obtain information about *terra rossa* in a typical location (Table 2).

At all locations the general characteristics of the occurrence were determined, geomorphic/speleomorphic characteristics were estimated and the site photographed. Field sketches of about half of the sample locations were produced, especially at sites where photographs did not seem to reveal crucial details to any reasonable extent. Soil colour was determined on the spot by reference to Munsell (2000) soil colour charts. Samples from each C horizon were taken for additional pedological and geological analysis. According to a design-based sampling plan, three independent sampling plots were chosen randomly for each soil. Three individual soil samples of two purely mineral horizons were extracted from each sampling plot, and placed together. Suitable parent rock samples were also taken at the same locations.

X-ray mineralogical analyses were carried out at the Department of Geology, University of Ljubljana (SLO). Pre-processing and other mineralogical procedures were done at the Geological Survey of Slovenia.

A sodium acetate buffer method was used to extract insoluble residue from the calcareous rocks. For each extraction 150 g tranches of material taken from 1000 g of ground sample were placed in glass dishes. Sodium acetate solution (1 M) was used to buffer acetic acid at pH 5.0 (Jackson, 1969) and the leaching solution was added to the samples 300 mL at a time. When the solution was consumed more leaching solution was added to keep the pH at 5.0. The process took about 30 days at room temperature with magnetic mixing at 600 rpm. At the end of the process residual solids were washed carefully with distilled water to remove any remaining leaching solution.

Grain-size was determined in water using a Fritsch Laser particle sizer Analysette 22.

The bulk mineralogy was determined on whole powder mounts. Samples of loamy material and insoluble residues were scanned using a Philips PW 3710 X-ray diffractometer with an 1820 goniometer, an automatic divergence slit, and a curved-crystal graphite monochromator. The instrument was operated at 40 kV and 30 mA using CuKα radiation. Bulk samples and clay fractions were scanned from 2 to 70° 2Θ with a step scan of 0.02 and step time of 1 s.

The clay fraction was later analyzed after vapour solvation with ethylene glycol for 12 h at 60 °C. Semi-quantitative mineralogical compositions of the bulk soil samples and clay fraction were calculated using the methods of Schultz (1964) and Mišič (1999).

Chemical compositions of samples were determined by Acme Analytical Laboratories Ltd.—Vancouver (Canada). Inductively-coupled plasma emission spectrometry was used to determine the main elements quantitatively and qualitatively, whereas inductively-coupled plasma mass spectrometry was used to determine trace elements. Carbon and sulphur were determined using a Leco CS444 element analyser. The results of chemical analyses were used to check and confirm the quantities of individual minerals in the samples.

Standard laboratory pedological analyses of loamy material were carried out at the Mendel University of Agriculture, Brno (Czech Republic).

Table 2
Mineral compositions of clayey materials and parent rock insoluble residues (in weight per cent)

Insoluble residues												
CODE[a]	Cal[b]	Chl	Dol	Gbs	Gt	Hem	Ill/Mnt R0	Kln	Mnt	Ms/Ill	Pl	Qtz
01 R	–	–	–	27.15	20.72	–	–	13.68	–	38.45	–	–
03 R	–	–	–	10.00	4.00	–	–	15.00	–	64.00	–	7.00
04 R	–	–	–	13.00	5.00	–	–	9.00	–	65.00	–	8.00
08 R	–	7.00	–	–	6.00	–	–	–	–	64.00	–	23.00
09 R	2.00	–	–	–	–	2.00	–	8.00	–	–	–	88.00
10 R	2.00	–	91.00	–	–	–	–	–	–	4.00	–	3.00
13 R	–	23.00	–	–	9.00	–	–	–	–	68.00	–	–
17 R	–	–	–	–	20.00	–	–	–	5.00	75.00	–	–
19 R	–	9.38	–	38.54	5.21	–	–	–	–	36.46	–	10.42
23 R	–	–	97.00	–	–	–	–	–	–	–	3.00	–
26 R	–	–	–	–	–	3.13	–	17.71	–	28.13	–	51.04
28 R	3.09	–	2.06	40.21	10.31	–	–	3.09	–	–	–	41.24
32 R	–	–	75.51	–	–	–	–	5.10	–	7.14	–	12.24
33 R	–	–	–	23.00	10.00	–	–	6.00	–	61.00	–	–
34 R	10.00	–	–	24.00	38.00	–	–	9.00	–	–	–	19.00
37 R	–	–	98.00	–	–	–	–	–	–	–	2.00	–
Number. of occurrences	4	3	5	7	10	2	0	8	1	11	2	10
Clayey material (*terra rossa*)												
01 C	–	34.00	–	6.00	7.00	–	–	43.00	–	10.00	–	–
03 C	–	30.00	–	6.00	10.00	–	–	40.00	–	14.00	–	–
04 C	–	–	–	–	15.00	–	18.00	61.00	–	6.00	–	–
08 C	10.01	–	–	–	7.00	–	24.00	36.00	–	23.00	–	–
09 C	–	–	–	–	5.90	–	33.31	28.13	–	17.19	–	15.47
10C	4.64	25.14	–	8.42	9.71	–	–	28.26	–	23.83	–	–
13 C	–	–	–	–	4.62	–	–	31.15	56.61	7.62	–	–
17 C	–	–	–	–	9.40	–	–	42.11	31.33	17.16	–	–
19 C	–	42.00	–	5.00	3.00	–	–	41.00	–	9.00	–	–
23 C	–	17.00	–	10.00	5.00	–	–	19.00	–	49.00	–	–
25 C	–	33.97	–	–	–	2.00	–	29.97	–	34.06	–	–
26 C	5.00	–	–	–	–	3.00	27.00	12.00	–	39.00	–	14.00
28 C	–	–	–	–	7.64	–	40.72	24.92	–	10.69	–	16.03
29 C	–	41.42	–	–	1.76	–	–	47.65	–	9.17	–	–
32 C	–	–	–	–	11.99	–	19.98	55.95	–	12.08	–	–
33 C	–	35.27	–	13.15	6.08	–	–	40.86	–	4.64	–	–
34 C	7.12	–	–	–	–	5.34	16.02	41.99	–	17.52	–	12.01
37 C	–	43.88	–	4.90	7.13	–	–	44.09	–	0.00	–	–
UMAG[c]	–	10.00	–	–	–	9.00	–	38.00	–	20.00	5.00	18.00
Number of occurrences	4	10	0	7	15	4	7	19	2	19	1	5

Note that minerals that appear only once are omitted from the dataset, as explained in the text.
Notes:
[a] Location codes are as shown in Table 1.
[b] International standard mineral abbreviations.
[c] Additional sample from Umag (Istria/Croatia); see text for explanation.

Considering that the pedological aspects are beyond the scope of the present paper, further details are omitted.

Basic statistical and cluster analyses of acquired data were performed by means of the Statistica (CSS©) software package.

4. Statistics of the raw data

Mineral compositions of insoluble residues and clayey material (*terra rossa*) from all sample locations were determined by X-ray diffraction (Table 2). Two of the Slovene insoluble residue samples (Čepovan and Komen) failed due to insufficient material being available. Nevertheless, the data obtained from the *terra rossa* are incorporated in some tables for purposes of comparison.

Based only upon the contrast between the presence/absence of individual minerals at each location, Sokal–Michener association coefficients (r_{SM}) (Lafitte, 1972) were computed between the finest fraction of the clayey material ("by default" coarser material was assumed to be "introduced") and the insoluble residues of the parent rock. If ordered according to increasing association values, three distinctive classes are recognizable, as shown in Table 3.

In the first group, zero association means that there are no similarities between the insoluble residues of the parent rock and the material on the surface. This is confirmed by very low and negative Pearson correlation coefficient values (r_P). Additionally, cluster analysis (Fig. 2) demonstrates a very low affinity between the Kočevska Reka and Višnja Gora *terra rossa* and the insoluble residue samples from the same sites. Both sites lie in Slovenia and are relatively close to larger outcrops of non-carbonate sedimentary rocks. Therefore, notably heterogeneous material is to be expected.

The intermediate group, weak association ($r_{SM} \leq 0.400$), comprises locations where there are some similarities between the mineral composition of insoluble residues and the material at the surface. Low Pearson correlation coefficient values (close to zero) confirm this statement. Inter-relationships illustrated by the dendrogram (Fig. 2) are on the level of between-group similarities; two "paired" samples (insoluble residue / *terra rossa* at the same location) only once fall within the same group. All locations except Tribuče lie in the Czech Republic and are of types where notably heterogeneous material is to be expected. In terms of occurrence type, the Sloup location is the only "vertical' (see further text) deposit and is evidently an exception. As it lies within the general area of the Sloupsko-Šošuvske caves, it is apparent that the effect is probably due to mismatching the type of occurrence. It might well be either an atypical unroofed cave, or a pocket (sensu Kukla and Ložek, 1958), infilled by material that poured

Table 3
Statistical relations between terra rossa and local insoluble residue mineral composition

No.	Name location	r_{SM}	General layout of the sampled occurrence	Type of sedimentary body	r_P
Zero association			$r_{SM}=0.00$		
23	Kočevska Reka	0.00	Lens	Horizontal	−0.1320
37	Višnja Gora	0.00	Lens to slope material	Horizontal	−0.1147
Weak association			$r_{SM}\le 0.400$		
10	Tribuče	0.250	Lens	Horizontal	−0.1503
8	Březina II	0.286	Unroofed cave	Horizontal	0.3170
9	Malomeřice	0.286	Lens	Horizontal	0.2640
13	Březina I	0.400	Slope material	Horizontal	−0.1528
28	Tman	0.375	In-filled cave	Vertical?	0.0716
32	Tetin	0.333	Lens/ possibly alluvium	Horizontal	−0.0648
34	Sloup	0.375	Cutter to pocket-like indentation	Vertical	0.0271
Strong association			$r_{SM}>0.600$		
1	Verd	0.800	Cutter	Vertical	0.2755
3	Laze	0.667	Cutter	Vertical	0.3326
4	Suchomasty	0.600	Cutter to pocket-like indentation	Vertical	0.1022
17	Skalka	0.750	Cutter to pocket-like indentation	Vertical	0.2726
19	Divača	0.667	Cutter	Vertical	0.1057
26	Hostim	0.667	Lens to slope material	Horizontal	0.5662
33	Lož	0.800	Cutter	Vertical	0.0866

into it, either from the surface or from a now-eroded cave (ghost cave), formerly located above the actual sample site (Šušteršič, 2007).

The third group contains reasonably close associations $r_{SM}>0.600$. Yet, though positive, predominantly low Pearson correlation coefficient values indicate that proportions between individual components within paired samples have been seriously distorted. Three locations are in the Czech Republic and the rest are in Slovenia. An obvious comment is that all but one of the sample sites are "vertical" (see below). Though formal similarities seem to be high, the general layout of the sample site (with an obvious predominance of coarse-grained fluvial material) does not permit a valid comparison.

Absence of intermediate r_{SM} values between the second and third group ($0.400>r_{SM}>0.600$ do not exist) implies a division into two major classes. One, termed "vertical sedimentary body type" VSBT, matches with the third group, whereas the other, termed "horizontal sedimentary body type" HSBT, covers the rest (Table 3).

A *t*-test of difference between the two groups confirms the idea of the existence of two groups ($p=0.0022$). Unfortunately, it cannot be expected that the two groups (VSBT versus HSBT) would be normally distributed, and other non-parametric statistics might well be more appropriate. A much more reasonable result is obtained by use of the Wald–Wolfowitz (STATISTICA™, 1998) test ($p=0.1205$). A working explanation is that VSBTs typically contain an observable admixture of local rock weathering products, whereas HSBTs do not, at least not in significant quantities. But even in the former case, the local component does not dominate.

Once the relationships between the clayey material and the insoluble residues from adjacent rocks, if related to occurrence type, have been to some extent established, it is necessary to ask, what are the similarities between samples of the individual media listed above? For this reason mineral composition data of parent rock insoluble residues and the present *terra rossa* were processed together. Allowing for the fact that the limited number of measurements does not permit deeper analyses, cluster analysis appears to be an appropriate tool to shed some light on any general similarities. As the data array is closed and missing values influence the dendrogram considerably, minerals that appear less than three times were excluded from the dataset. The expression $1-r_P$ (1—Pearson correlation coefficient) was chosen as providing the best estimate of linkage distance (d). The value $1-r_P<0.4$ was set in advance as the absolute grouping criterion. Mineral composition data of a "typical" *terra rossa* sample from Umag (Istria, Croatia) were added to the data set as an "standard" to which other samples can be compared.

The dendrogram (Fig. 2) turns out to display a very simple pattern. Four groups, labelled A, B, C and D, are apparent. Only three seemingly rogue samples of insoluble residues remain, namely Březina I, Březina II and Skalka. Nevertheless, they are interrelated on the level $d<0.4$. It is interesting to note that their maximum mutual physical distance apart is less than 1 km.

Seemingly, D is the most coherent group ($d>0.01$). It encompasses four insoluble residues, all of them characterised by large amounts of dolomite. Statistical distance from the other samples is greater than 1, which means that r_P is negative. This indicates that the presence of dolomite in the insoluble residue might completely obscure the

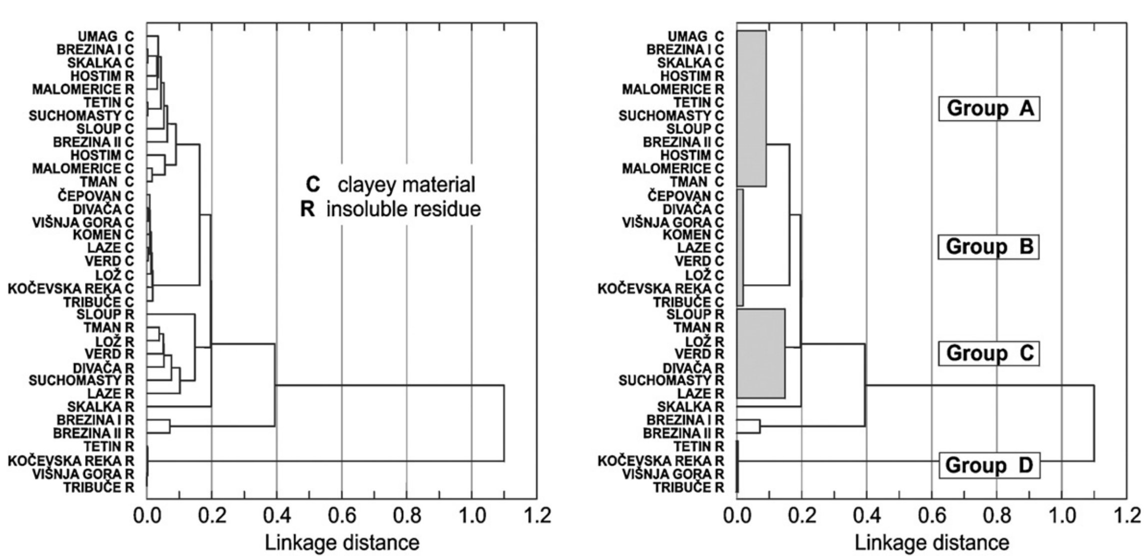

Fig. 2. Sample locations grouped according to their mineral composition (C—clayey material; R—parent rock insoluble residues). Left: Relations between individual samples; right: Major sample groups and relations between them.

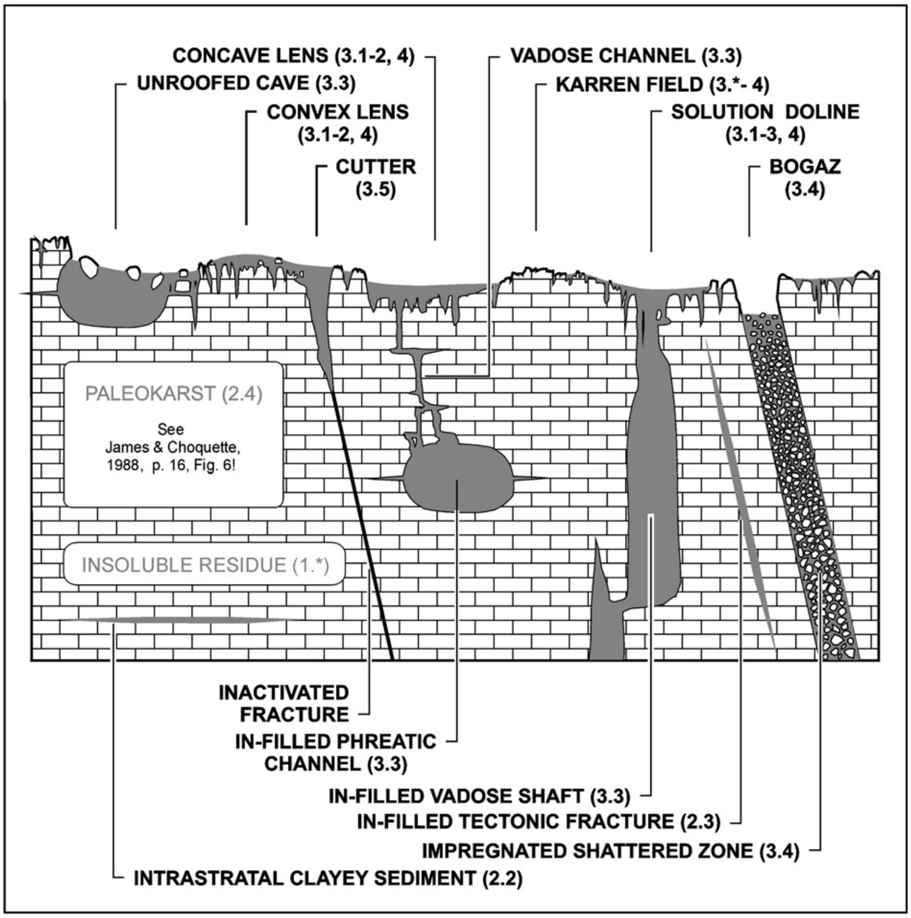

Fig. 3. Some of the more important sources of *terra rossa* material. The coding scheme is explained in Section 5. For definitions see text and Choquette and James, (1988, p. 16, Fig. 6).

contribution of other insoluble components. However, the possibility that the other components might also be somehow related cannot be ignored.

The next most coherent group is B, characterised by internal statistical distances $d<0.05$. Without exception it covers all *terra rossa* samples from Slovenia, indicating a relative uniformity of Slovenian *terra rossas*.

The third group is A, with internal statistical distances $d<0.1$. All clayey samples from the Czech Republic are gathered there, including insoluble residues from Hostim and Malomeřice. For the latter two, relatively large quantities of quartz are as characteristic of the clayey material as of the insoluble residues, and this might obscure other signals. Nevertheless, the Hostim location has been mentioned before as being somehow exceptional, and Malomeřice is characterised by large quantities of chert aggregates. Perhaps surprisingly, the Umag "control" sample of "standard" *terra rossa* also falls within group A.

Groups A and B are linked on the level $d<0.2$. This reveals that mutual differences between *terra rossas* are smaller than those between insoluble residues. In the other words, it indicates that *terra rossas* in general are relatively unified, though sensitive to regional locations.

The remaining group C includes insoluble residues only. In contrast to the former groups the members are not location dependent. Most of the inner statistical distances are relatively greater than before, while nevertheless, being small ($d<0.2$) in their own right, perhaps indicating comparable sedimentary conditions of the parent rocks.

- With respect to the contrast between *terra rossa* and insoluble residue, both basic groups (with two easily explainable exceptions) are nearly perfectly homogeneous.
- The former basic group can be further split in two on a regional basis. In this context the Slovenian subgroup is much more coherent than the Czech.
- Statistical relationships between insoluble residues are weaker, and the relationships are not location dependent.

5. Possible sources of *terra rossa* material

Starting from the two alternative options of *terra rossa* origin, and temporarily ignoring Merino and Banerjee's (2008) ideas, a straightforward deduction is that *terra rossa* material (Fig. 3) is basically:

1. Parent rock weathering products (PRWPs). This category covers the material, part of the rock matrix, released during gradual chemical decay of the rock. Dimensions of individual crystals are within the range of calcite crystals or smaller. Its origin might involve material from at least two sources. Simply, the components of the PRWP might be original and unchanged insoluble minerals, precipitated directly from sea water, that have survived deposition, diagenesis and subsequent dissolution of the surrounding limestone matrix. Geochemically or mineralogically, however, it is also possible that some of the insoluble material is pre-existing rock/mineral debris carried into the carbonate depositional basin by wind or water.

1.1 Platform depositional environments gave rise to the development of some of the best defined karsts in the world, approaching the ideal conditions of the PKM. Such conditions permit sedimentation of a limited suite of Al and Fe hydroxides. Only these may be termed typical admixtures to the parent rock. Synsedimentary silica may be much more abundant, but it is questionable to what extent silica-rich carbonates can be considered as "karstic" rocks. Also, silica of this kind generally appears as larger crystals, globules or similar aggregates, which places them into group 2.

1.2 Clay minerals (or, more generally, phyllosilicates) are more abundant within *terra rossas,* but they are not a typical product of limestone sedimentary environments and diagenesis. When present in the insoluble residue they must, therefore, be considered as admixed impurity minerals. Their (potential) presence in the residue reflects "contamination" resulting from individual local micro input and sedimentary conditions. Consequently, they may be considered as incidental admixtures to the parent rock.

Mineral grains of PRWP type are relatively uniformly dispersed through the rock, so that they are detectable in the laboratory, for instance by dissolving typical hand specimens. It is vital to acknowledge that PRWPs present within carbonate rocks might not represent normally expected carbonate rock constituents (type 1.2 above).

2. Neighbouring rock removal products (NRRP) differ from PRWPs in their distribution within the rock mass. Insoluble material gathers into aggregates set within the otherwise possibly completely pure carbonate mass. Such accumulations are released when erosion removes the surrounding rock. Four basic types can be identified:

2.1 Synsedimentary deposits of chert and other silica minerals. Such material can inhibit karstification significantly.

2.2 Bedding plane surfaces within even the purest parts of the Dinaric carbonate sequence are marked locally by approximately millimetre-thick clastic layers (Mišič, 1999). Compared to the total volume of the carbonate beds, even the cumulative amount of clastic layers, or films, is negligible, but it is quite possible that it exceeds the amount of PRWPs.

2.3 Freshly-opened quarry faces in many karst regions are neither white nor grey. Instead they are reddish, due to staining derived from red in-fillings of tectonic fractures and bedding plane partings that have not been subject to karstification. Ongoing studies (Zupan-Hajna, 1989, 1997) have revealed a highly heterogeneous composition, ranging from fine calcite silt to clay minerals, though the general appearance is quite uniform due to the reddish, hematite, stain.

2.4 During early diagenesis eustatic oscillations of sea level could bring some portions of the sedimentary mass above sea level. During exposure to precipitation the full suite of karst phenomena will develop, including sedimentation of insoluble material either in newly formed caverns, or on the surface, say as accumulations of *terra rossa.* After resumed immersion new carbonate mud would fill the caverns, and carbonate sediment cover the inherited karst. Eventually, just as the early "parent rock", the sediments will develop into solid rock.

NRRPs usually appear also in comparatively larger bodies trapped between the neighbouring carbonate rocks. The masses are cemented and disintegrate only where and when subjected to ongoing denudation. So, release of individual particles is gradual, going hand in hand with dissolution of rock cement. Because somewhat larger bodies are scattered randomly throughout the rock mass NRRPs cannot necessarily be detected when dissolving random hand specimens of parent rock, but they are commonly visible to the naked eye.

3. Subjacent or surrounding rock removal products (SRRPs) are generally non-cemented clastic sediments lying or exposed on the top of the rockhead. Such material is obviously allochthonous or para-autochthonous and reworked by pedogenetic processes to a lesser or greater extent. During ongoing surface lowering loose material will pour into negative forms of all types and concentrate there. In contrast to NRRPs the SRRP masses are not cemented and are prone to supporting throughput of precipitation water, and hosting the roots of vegetation. Where the loamy material is in contact with rockhead, chemical denudation becomes more effective than on bare rock surfaces (Gams, 1981; Zseni et al., 2003). Whereas PRWPs and NRRPs tend not to accumulate in larger bodies, and perhaps can't influence the denudation process, SRRPs are large enough to become active agents in rock weathering. Several arrangements appear obvious:

3.1 Before reaching underlying, karstified, carbonates fluvial (or glacial) "caprock" erosion removes weathered (non-karstic) material, on the surface. Later, when ongoing lateral denudation has opened the first windows through the caprock to the underlying limestone, there is a significant change in the style of erosion. The pre-karstic lateral denudation process(es) can continue only until underground drains can remove all of the autochthonous and allochthonous water that gathers there. Except in the close vicinity of larger active cave openings, local precipitation water is no longer capable of removing weathered material from the remaining patches of caprock. In tandem with the progressive lowering of rockhead, partly reworked material would gradually "shift" downwards. Such material would accumulate in lenticular bodies, containing clayey and sandy material (depending upon the original rock type), as well as fragments of unweathered rock. Also, this material may infiltrate all types of karst voids that it encounters on its way downwards. At Tribuče (Location 10), pieces of relatively well-preserved sandstone are found within a *terra rossa* body. Presently, such rock is known in the Kanižarica coal mine only, more than ten kilometres away. According to conditions on the karst surface, accumulations of chert globules and concretions fall best into the same group. Quantities of such material may be quite large, depending upon local conditions.

3.2 Weathered relics of allochthonous non-carbonate sediments on the karst surface might be of various origins—fluvial, glacial or aeolian. Rivers that once incised the non-carbonate caprock generally carried a mechanical sediment load, leaving piles of sediment in calmer positions. Similar arguments apply to trans-environmental rivers (sensu Garner, 1974, p. 708) emerging from non-karstic surroundings but cutting through karst areas. Glacial tills are well known in northern Europe, and elsewhere in high mountain karsts. Just like weathered remnants of the caprock, such material can migrate downslope, gather in lenticular bodies and, potentially, penetrate karst voids. Again, quantities of this type of material can be quite large. Perhaps the most widespread are air-borne sediments, in the largest quantities originating either from actual deserts and Pleistocene barren lands, or air-fall from volcanic activity. They may appear at any location, covering large areas, and they can admix with every type of soil or clayey material lying on the karst surface. In the absence of larger quantities of other fine-grained material, such sediments can make a major contribution to deposition on the karst. Bauxite researchers in particular (Comer, 1974, 1976; Guendon and Parron, 1985) acknowledge volcanic ashes as an important contributor.

3.3 Unroofed (denuded) caves (Šušteršič, 1999, 2007) are closely related to underground karstification. The most enduring and characteristic infill of unroofed caves is flowstone, which (if present) generally covers the walls, but it does not contribute to the *terra rossa* quantum. Other unroofed cave deposits comprise various clastic sediments, spanning the continuum between fine loams and the coarse-grained fluvial sediments of allogenic underground rivers (Šušteršič, 2007). When all of the parent rock has been removed, sedimentary fill in unroofed caves may survive at the karst surface in the form of relatively small and localized lenticular bodies (Šušteršič, 2007, p. 129, Fig. 4). As surface lowering proceeds the material may admix with any other karst surface accumulations and becomes hardly detectable.

3.4 Bogazes (US Environmental Protection Agency, 2002, p. 22) might be important sources of *terra rossa*. Basically they are the central, shattered, zones of sub-regional, strike-slip, faults. The rock mass between the smooth, bounding rocky walls on both sides of the fault zone is commonly ground to coarse gravel. Bogazes are a few metres wide and can be several kilometres long. Their vertical extent is unknown—evidently most of them reach a few hundred metres deep. High porosity values allowed transport and accumulation of loamy material of whatever origin. Intensive corrosional activity usually reduces the gravel in the topmost c.10 m-"deep" portion to a small number of individual, secondarily rounded, stones floating in a brownish or reddish loamy mass. Well-developed bogazes thus look like nearly straight canyons a few metres deep, with smooth walls and an uneven floor.

3.5 Cutters (in the sense of White, 1988, p. 43, Fig. 2.21; US Environmental Protection Agency, 2002, p. 53, option 2) seem to differ from the SRRPs discussed above primarily because of their geometry. They are basically planar bodies of loamy material wedging into the parent rock in more or less perpendicular fashion. In this respect they differ markedly from other types of structures that contribute to producing corrugated rockhead morphology. They commonly reach 10 m in depth and are generally somewhat less than a metre wide at the top. Their longitudinal dimension is more characteristic, exceeding tens of metres in many cases. Observation of fresh sections in road cuttings (White, 1988, 43, Fig. 2.21) makes it clear that in most cases they are enlarged tectonic fractures. In origin cutters are inherently surface or, more specifically, subcutaneous karst features, and must not be confused with denuded, secondarily infilled, vertical, shafts that are characteristically underground features (Klimchouk, 1995). The crucial difference is that infilled, vertical shafts can penetrate to much greater depths. By volume individual cutters are much smaller than the sedimentary bodies described in types 3.1 and 3.2, and they might well be found underlying them, or even beneath partly decayed unroofed caves. SRRPs are exotic sedimentary bodies on/in the karst surface, the mere existence of some of them (3.3, 3.4) being conditioned by the karst. Because contributions of material released from PRWPs and NRRPs can be negligible, location on the karst ensures that SRRPs 3.1–3.4 more or less retain their original mineral composition, whereas the situation with cutters is somewhat different. Piles of SRRPs are favourable to vegetation colonization and growth and, consequently, to CO_2 production. They are active agents in the ongoing karst surface lowering process.

4. Alien, surface intercepted, material (ASIM) differs from the sediments described above in the way that information about its origin has either been lost or has never existed. In form such materials resemble SSRPs, especially HSBT types 3.1 and 3.2. Component material might have been mixed at the time of sedimentation, or during ongoing surface lowering. Gradual bedrock removal at rockhead leads to debris accumulation in lower areas. To some extent winnowing and, especially, washing away of the finer fractions of the unconsolidated materials overlying rockhead are evident. Concurrently, loamy sediment bodies intercept newly introduced aeolian debris and incorporate fragments set free from PRWPs and NRRPs. Much of the sediment preserved on the karst surface fits best into this group.

6. Storage ability of the karst surface

Effectively the karst surface is just a sieve, where loamy material from a number of sources accumulates. An obvious problem remains concerning how small mineral grains remain trapped on the karst at all. An equally obvious explanation is that either vegetation or mantles of coarser, or minimally cemented, mineral particles – contained especially in some NRRPs, SRRPs and ASIMs – protect finer fractions of various origins from rain drop impacts, and thus from being washed away. Loam-covered reaction surfaces are exposed to the effects of laterally moving epikarstic water (Williams, 1983), which might bring about simultaneous washing of the PRWPs just released.

Problems of origin and accumulation of *terra rossa* components are less evident in the case of NRRPs. Whereas the parent rock detachability is still weathering-limited, clastic layers within bedding plane (2.2) and palaeokarstic (2.4) voids can support more abundant vegetation, which can moderate possible washing out. The issue of the now slightly calcite-cemented red in-fillings of tectonic fractures and bedding plane partings (2.3) in the Dinaric Karst is somewhat different. Even though all such material is not insoluble – Zupan-Hajna (1989) for example recognized many hematite-coated calcite grains – the total volume of infilled fractures is not negligible.

Due to their basic geometry a fundamental difference emerges between subgroups of subjacent / surrounding rock removal products (SRRPs). Weathered caprock-derived material (3.1), weathered relics of allochthonous non-carbonate sediments (3.2) and unroofed cave in-fillings (3.3) basically appear in flat, more or less lenticular bodies. The horizontal dimension predominates (HSBT) and the reaction surface, i.e. the PRWP and NRRP producing area, is roughly horizontal too. Soon after a body of SRRP or ASIM has somehow covered the pre-existing bare rock surface, storage of PRWPs and NRRPs become more likely. However, if compared to the volume of the overlying SRRPs or ASIMs, the quantity will usually be minimal. Material belonging to subgroups 3.1 and 3.2 is perhaps the greatest by volume, but it soon changes to ASIMs.

Radinja (1967) interpreted large quantities of quartz pebbles spread all over the Kras plateau (southwestern Slovenia) as the remnant sediments of earlier, karstified, surface rivers. Mihevc (2000) showed that the sediment actually originates from numerous unroofed caves (3.3). He estimated that the amount of *terra rossa* set free from unroofed caves in this region exceeds 30% of the total soil. In a statistical study of the caves cut during motorway construction between Vrhnika and Postojna (Slovenia), Šušteršič (1978) revealed that about 95% of the vadose voids in the solid rock were filled with sediments, washed in from *terra rossa* bodies on the surface.

In terms of their storage capabilities bogazes are in some respects similar to unroofed caves. They might provide the largest individual storage sites for *terra rossa*. As their surface exposure is of limited extent their full importance is yet to be assessed.

Roadcuts in motorways traversing the Dinaric karst provide direct evidence that, among VSBTs, subtype 3.5, cutters are most common. They range from some decimetres to a few metres in width and up to a dozen metres deep, whereas their longitudinal dimensions can be much larger. Almost inevitably they are seen in cross section, so it is most helpful to discuss them in this way. Most commonly they are explained as being derived from rock fractures that became wide enough to allow clayey material from the surface to pour into wedge-shaped voids. In this context chaotic mixing during the parallel denudational surface lowering and downward migration of the void/fill is less likely. This explains to some extent why the association between parent rock residue and vertical-type occurrences (Table 3) is greater than in other cases.

SRRPs and ASIMs might be either ubiquitous or only locally present. Their total quantities usually dwarf the amounts of local PRWPs and NRRPs, and make them barely detectable. The effect is accentuated because loamy bodies adapt readily to rockhead lowering, decant into local depressions and change permanently into ASIMs. Expectation is that the proportion of PRWPs and NRRPs will be relatively greater if the agent supporting accumulation is just vegetation, especially mosses. Nevertheless, the influence of aeolian material, and especially air-borne dust, can never be ignored.

Larger lenticular SRRP and ASIM bodies are even more capable than VSBTs of retaining precipitation water and thus supporting enhanced vegetation growth. In the longer term increased soil CO_2

production would trigger relatively faster removal of rocky basement and, thus, formation of terrain depressions (Gams, 1981). It might also be imagined that increasing the relative depression size would trigger positive feedback and attract additional loam from the immediate neighbourhood, but this is yet to be proved. In the Dinaric Karst, drawdown solution dolines can readily be derived from unroofed vertical shafts (3.3) (Klimchouk, 1995), but these are a fraction of all the depressions. In the present authors' experience, the rockhead is much more corrugated within depressions derived from loam bodies than in surrounding areas.

- Parent rock weathering products (PRWPs) are released in extremely small quantities, so that they cannot survive exposure on the surface without a protective mantle of either larger loamy bodies or just of vegetation. Their behaviour is entirely passive.
- Neighbouring rock removal products (NRRPs) behave like PRWPs, but in some circumstances they can survive on the surface without any additional protection.
- Most subjacent or surrounding rock removal products (SRRPs) appear in large enough quantities to survive at the surface. Additionally, positive feedback might even increase their attraction and acquisition of materials from other sources. Their role on the karst surface is active.
- Alien, surface intercepted, materials (ASIMs) behave in similar fashion to those above, but information about their origin has been lost. During ongoing denudational surface lowering, most SRRP bodies pour into local depressions, mixing up and thus changing into ASIMs.

7. Discussion

It transpires that the karst surface is primarily a receptor of loamy materials, which are subsequently exposed to specific processes, largely unrelated to the "original" karst rock constituents. Only the loamy fills of cutters are to some extent closely related to the parent rock, whereas other *terra rossa* bodies are less closely related or not related to it at all. It appears that cutters have not been considered systematically in the past, having normally been explained as relatively short-lived, unimportant, indentations into the rockhead surface. It is generally accepted that they develop from rather more pronounced, vertical or subvertical joints that begin to collect loam when wide enough. A positive feedback loop will establish, based on the cascade: larger volume of soil pile → more vigorous vegetation → greater production of CO_2 → enhanced corrosion activity → new space → attraction of additional loam. In such situations cutters of very different dimensions would be expected, some reaching to great depth.

In reality cutters are rarely deeper than about 10 m. Where they do reach greater depths the extensions are either related to purely underground cavities that were encountered and incorporated during lowering, or they are actually bogazes. This seems to provide evidence that cutter formation began from scratch relatively recently, or that negative feedback has slowed down propagation at some stage.

The former idea introduced above includes a naïve supposition that surface lowering during cutter development is negligible. Consider different corrosional rockhead lowering rates on the neighbouring terrain surface and within the loam filled depressions, v_S and v_D respectively, expressed in mm a^{-1}. Set $v_D > v_S$. Let D be the relative depression depth, and H the amount of surrounding surface lowering since commencement of depression development. It is straightforward to derive that $H = Dv_S/(v_D - v_S)$. Set the difference between the two rates $\Delta = (v_D - v_S)$. Then, $H = Dv_S/\Delta$. In other words, during the time needed for development of the depression of depth D, the surrounding surface lowering H will be larger if the difference between the two rates is small, and smaller if the difference is large. The amount of general lowering during a period of overall terrain depression would become negligible only if Δ were very large. It appears from data presented by Zseni et al. (2003) that the differences in pH measured on clints and within grikes do not imply considerable Δs.

An alternative explanation of the limited vertical dimensions of cutters is the possible existence of negative feedback, which would inhibit the initially fast downwards propagation. After a steady state had been achieved cutters, formed initially along predetermined structures, would propagate downwards following the same structure and retaining the same wedge-like shape without losing their identity.

Consider a 25 cm-wide (at the top) and 500 cm-deep, indentation of regular wedge-like shape. Let the parent rock insoluble residue content (PRWP) be 1%. Specific densities of the rock and the insoluble residue are taken as being equal. If the wedge is widening uniformly, perpendicular to the sides, it becomes 27 cm wide at the top and 540 cm deep after both walls have retreated 1 cm horizontally beyond their original positions. The original cross-sectional area of the wedge has increased from 6250 cm^2 to 7290 cm^2. If the insoluble residue released remains on the spot it occupies 1% of the total removed volume, i.e. it takes up 10.4 cm^2. Consequently, as the void enlarges and existing fill relocates to fill the new space below, additional space about 40 cm high with cross-sectional area of about 1030 cm^2 is created at the top of the wedge and this is available to accommodate new material (predominantly ASIMs) arriving from the surface.

Before negative feedback has begun to operate PRWPs in cutters would become increasingly less detectable if total mixing occurred. However, due to specific cutter geometry, concentration of PRWPs would be expected deeper within the cutters, whereas ASIMs would be more likely to remain at the top. During their formative phase, cutters are net collectors of dominantly exotic material, which is in striking contrast to the findings presented in Table 3.

Note that if $v_C > v_S$, a cutter's reactive surfaces will increase during its development, while the available quantity of precipitation water remains the same. This might slow the process down until v_C becomes equal to v_S. From this point the cutter will propagate downwards at exactly the same rate as the adjacent surface. The cutter's upper rim will continue to recede in parallel with the lowering land surface, exposing the uppermost layer of loamy fill to the effects of surface erosion. Assuming that PRWPs are produced continuously at the reaction surfaces, the share of parent rock originated material in the loamy fill would increase, in the extreme case replacing infills of other origins completely. Only then would a cutter achieve its steady state. This will happen when the cutter has actually migrated downwards by the equivalent of 99 times its actual preserved depth. In the Ljubljanica basin (Šušteršič, 2000), where the mean annual denudation rate (Gams, 1966) is approx. 65 m Ma^{-1}, a 10 m-deep cutter would need at least 15 Ma to be completely filled with PRWPs, and so, achieve its steady state.

More general aspects of *terra rossa* incidence on the karst surface and its geomorphic role, discussed below, are mostly based on information from the Dinaric Karst of southern Slovenia (Gams, 2003), as its actual mode of occurrence is close to the hypothetical statements of the PKM (Šušteršič, 1996). The two studied karst areas in the Czech Republic are too small to allow the exclusion of obvious adjacent non-karstic influences (or of former overlying deposits) upon the present situation.

An approximate estimate of the bulk surface *terra rossa* mantle thickness of the Dinaric Karst of Slovenia is 0 to 70 cm. For the Alps the figures are 0 to 50 cm, and for the Ljubljanica basin > 50 cm (Szramek et al., 2007). A general review of the actual thicknesses of such accumulations bears no relation to the possible quantities of rock presumably dissolved. Layers of *terra rossa* a dozen metres or more in thickness lie on top of the Upper Cretaceous limestones, whereas (stratigraphically) 5 km "lower" the *terra rossa* thickness might be negligible, even though the general circumstances appear comparable.

A more tangible observation appears to be that the overall thickness of the *terra rossa* mantle on a well developed karst surface is somehow controlled by local relief. In southern Slovenia an approximately inverse relationship between the local relief and *terra rossa* mantle thickness is clear. This might imply that shrinking of the vadose zone brings about an increase in the loam storage ability of the karst surface, but precise functional relationships are yet to be sought. Thus, the primary question is not whether *terra rossa* is a weathering residue of limestone, but what controls the quantities of loamy materials, whatever their origin, on the karst surface, especially in climax conditions.

The results of the present research appear quite straightforward, yet they must be viewed with great caution. This analysis has covered only two aspects of the *terra rossa* problem, i.e. insoluble parent rock residue (PRWPs) and the basically undefined mixtures of loamy material from several possible sources (ASIMs). Though seeming to be reliable statistically, these findings represent far too small a sample to allow valid generalizations to be drawn. Recent findings by Merino and Banerjee (2008) suggest completely new ways to interpret the geomorphic role of *terra rossa* and might to some extent change the present considerations. Until more detailed studies have taken place this attractive issue remains open.

- Among the different types of *terra rossa* accumulations VTSBs, especially cutters, are the most likely to contain traceable quantities of PRWPs.
- Cutters might not be phenomena that exist only temporarily, but rather they change their position downwards, in step with long-term steady state lowering of the karst surface.
- The relative share of PRWPs in a cutter decreases during its initial development stage, but it increases until steady state geometry has been achieved. Theoretically, in completely steady state conditions cutters would contain PRWPs only.
- Dimensions (depths) of cutters do not contradict the hypothesis about steady state lowering of the southern Slovenian karst.
- Relative concentrations of PRWPs in cutters indicate that a considerable time has passed since the achievement of equilibrated cutter geometry, and that since then they have evolved under steady state conditions.

8. Conclusions

- *Terra rossa* is not an inherent karst feature but rather an attribute of the inevitable configuration of any karst geomorphic system.
- Explaining the existence of *terra rossa* on the karst surface involves solving a storage problem rather than a source problem.
- The composition of *terra rossa* includes arbitrary contributions from several sources, to some extent unified under conditions induced by a specific microenvironment, i.e. karst geomorphic system development.
- Direct comparison of insoluble parent rock residue extracted from the neighbouring rock, and loamy material accumulated nearby involves a hidden supposition that insoluble residue derived from stratigraphically higher strata are essentially the same as the insoluble material in the intact, sampled, rock. Depending upon the stratigraphy this condition might be fulfilled, or not.
- Original limestone weathering products (PRWPs) are produced at a very slow rate and they take time to accumulate at the surface in quantities that make them detectable among other types of loamy sediment.
- Depressions of whatever origin that have once accumulated a significant quantity of *terra rossa* might be long-lasting features persisting during steady state lowering of the karst surface, but their original bedrock geometry is completely lost.
- Traceable quantities of insoluble parent rock residue in cutters suggest that general surface lowering in the Dinaric Karst of southern Slovenia has continued without important interruptions, i.e. under steady state conditions. Evidence from the Czech sites is more difficult to interpret as they are exposed to too many non-karstic influences.
- Clear compositional groupings of *terra rossa* (shown in Fig. 2) are quite obvious, whereas there is much more variation in the composition of insoluble residues. Consequently, in spite of their evidently very different origins, clayey materials evolve towards a similar final composition. So, it appears that during *terra rossa* evolution, diagenetic factors prevail over the origin and original nature of the source material.

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